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The organic Rankine cycle power systems market: Recent developments and future perspectives

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A B S T R A C T

This work presents an up-to-date overview on the recent developments in the Organic Rankine Cycle (ORC) industry. Information from more than 30 manufacturers, representing a total of almost 2900 projects have been collected and analyzed providing information on trends in the past and the market evolution during the last four years in terms of installed capacity and installed plants divided by application, macro region and manufacturer. At the end of 2020, the cumulated installed capacity of ORCs was 4.5 GW. Since 2016, the overall ORC market increased by 40 % (+1.18 GW) in terms of installed capacity and by 46.5 % (+859) in terms of installed plants. Regarding the capacity increase between 2016 and 2020, the largest increase is due to geothermal application (+972 MW, +45 %) with 74 new plants, while waste heat systems have the largest growth in terms of the number of installed systems (630 plants, +208 %) with an installed capacity of 125 MW. The installed capacity of biomass ORC systems increased by 20 % (69 MW), while the number of installed plants increased by 22 % (77 plants).

Additionally, a market survey was conducted, and ten established ORC manufactures contributed their perspective on the ORC market. The results highlight that, despite COVID-19, the current market situation is in good shape and that the majority of the manufacturers have positive expectations concerning the future development. Central and Eastern Europe as well as the ASEAN region are rated as the regions with the highest growth potential. Geothermal energy and small waste heat installations are expected to be the most relevant heat sources for the coming years.

1. Introduction

1.1. Organic Rankine cycle technology

In order to limit global warming to a maximum of 1.5 °C, even more rapid and holistic changes of the global energy system become inevitable. Besides the increase in PV and wind power generation systems, the use of reliable low and medium temperature heat sources is an important building block in the energy transition in order to meet current climate goals [1] since there is a tremendous technical potential for the conversion of low and medium temperature heat, such as from geothermal reservoirs, solar systems, biomass combustion or waste heat sources. In this context, the Organic Rankine Cycle (ORC) is a key technology for exploiting these low to medium temperature renewable and sustainable energy sources. As discussed in detail by Macchi [2], the ORC outperforms both gas cycles and water/steam cycles at rather low heat source temperatures and small to medium plant sizes. Colonna et al. [3] highlight that the ORC technology is probably the most flexible applicable technical solution for the utilization of external thermal energy sources. In addition, ORC systems are suitable for the combined generation of power, heating and/or cooling. A more detailed description of the history on ORC power systems and their technical options are presented by Bronicki [4] and Astolfi [5].

The basic working principle of an ORC corresponds to that of the Clausius Rankine cycle. The difference is the applied working fluid in the closed cycle. Instead of water, an organic working fluid is applied, enabling the utilization of lower temperature heat sources, which cannot be effectively and economically exploited with water. Fig. 1 visualizes the main components of a simplified standard single-stage subcritical ORC system and the corresponding temperature-entropy diagram. Within the heat exchanger (1 → 2), the working fluid is preheated, evaporated and often slightly superheated. In the next step, the vapour-phase working fluid expands to a lower pressure level in an expansion device (e.g. a turbine). In the next process (3 → 4), the working fluid is desuperheated, condensed and often slightly subcooled. Finally, the working fluid pump pressurizes the working fluid (4 → 1).

ORC systems can be characterized among others based on their installed capacity and heat source temperature. Regarding the ORC capacity, this work follows the definitions from Macci [2], who sees the threshold value between small and medium scale ORC systems at around 50 kW, while large-scale ORC systems have a capacity above 1 MW. A similar clear distinction for the heat source temperature level is not

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possible, since the scientific community uses these terms differently depending on the actual heat source types. For example, a geothermal heat source with 200 °C would be considered as a high temperature heat source, while it would be a rather low temperature source for a waste heat recovery system. Thus, the meaning of the terms low/medium/high temperature depends also on the considered ORC heat source type.

1.2. State-of-the-art and current trends

The following section provides a compact introduction to the state-of-the-art for the most relevant heat sources exploited by ORC power systems.

1.2.1. Geothermal energy

Deep geothermal energy has a tremendous worldwide potential [6] and ORC systems are the most common power generation technology for geothermal heat source temperatures below 180 °C [7]. ORC technology is most commonly used to exploit low- to medium-enthalpy liquid dominated geothermal heat sources or as bottoming cycle of high-enthalpy sources. Optimizing the thermodynamic plant configurations and working fluids for different geothermal heat source conditions in order to improve the economic performance has a long tradition in both academia and industry.

Subcritical ORC systems are most common in commercial large-scale geothermal systems. The same applies to two-staged ORC systems, which enable an improved temperature match between the heat source and the ORC and an improved utilization of the heat source [8]. Both effects can result in a significantly higher achievable power output. A detailed thermodynamic description of a commercial subcritical two-staged ORC system is presented by Heberle et al. [9] for the 5.5 MW_{el} ORC power plant Kirchstockach (Germany) manufactured by Turboden, while another example from Exergy can be found in [10]. From a thermodynamic point of view, supercritical ORC system are often favourable thanks to a better match between the temperature profiles of the geothermal brine and the ORC systems [11]. However, the higher required pressure level within the ORC power system increases the material stress and might have a significant effect on the investment costs and, as a result, they have been adopted only by TAS in some North American geothermal fields.

Due to the rather low heat source temperatures, the condensation pressure has a significant effect on the efficiency and the power output. The application of wet cooling towers might be economically favorable compared to a dry air-cooled condenser, but depends on several factors such as the availability of and the associated costs for the consumed water [12]. However, especially in dry regions, the shortage of water may be a barrier for an ecologically reasonable use of water intensive cooling concepts. Therefore, most of the geothermal power plants adopt dry air cooled condensers with a large footprint. Solutions implementing advanced condensation concepts focusing on no [13] or only small water consumption [14] are of high interest to further increase the ORC power output in case of high ambient temperatures and water scarcity.

Besides solely generating electricity, geothermal energy is often utilized for combined heat and power (CHP) production [15]. Such CHP systems are characterized by significant periods of part-load operation due to variations in heat demand. Thus, more advanced and flexible plant configurations are pivotal to further improve the performance of geothermal CHP systems. Advanced CHP systems are currently investigated by many researchers, both theoretically (c.f. by Habka and Ajib [16] or van Erdeweghe et al. [17]) and experimentally (c.f. by Eyerer et al. [18]). In light of the increasing cooling demand, the application of geothermally driven absorption chillers is an attractive alternative to electricity-intensive compression chillers. Hence, efficient and flexible geothermal trigeneration systems that can provide cooling, heating and power generation might be of high interest in the future. Potential tri- or polygeneration plant concepts are investigated by several authors, such as Pastor-Martinez et al. [19]. However, as highlighted by Lee et al. [20], the significant part-load effects due the changes in heating and cooling demand are neglected in most studies.

Currently, the commercial utilization of deep geothermal resources is mainly limited to so-called hydrothermal resources, which require the presence of water-bearing layers with a naturally sufficient hydraulic permeability [21]. In order to overcome this constraint of geothermal power systems on certain geological favorable regions, so-called Enhanced Geothermal Systems (EGS) are an ongoing research topic for the application of geothermal power production, since the technology could be applied worldwide and location-independent [22]. Other promising future concepts for geothermal power generation might be the focus on the energy extraction from deep wells in hydrocarbon resources [23] and the application of closed loop borehole heat exchanger systems [24]. However, such systems might have rather low heat source temperatures, which pose challenges for an economic application of ORC systems.

1.2.2. Waste heat recovery

ORC systems can also enable the commercial utilization of waste heat with low heat source temperatures, which do not allow a commercial application of a steam power cycle [25]. Typically for ORC waste heat recovery (WHR) systems are heat source temperatures below 350 °C [26]. Depending on the type of waste heat source, the heat carrier/effluent can be a fluid, steam or flue gas. In case of flue gases at high temperatures, an intermediate oil circuit is commonly installed for stationary ORC systems. Such an intermediate circuit can significantly simplify operation and control as well as increase the lifetime of the ORC heat exchanger, due to lower thermal stresses and reduced corrosion and fouling problems caused by the flue gas [27] while limiting working fluid decomposition in heat exchanger hot spots.

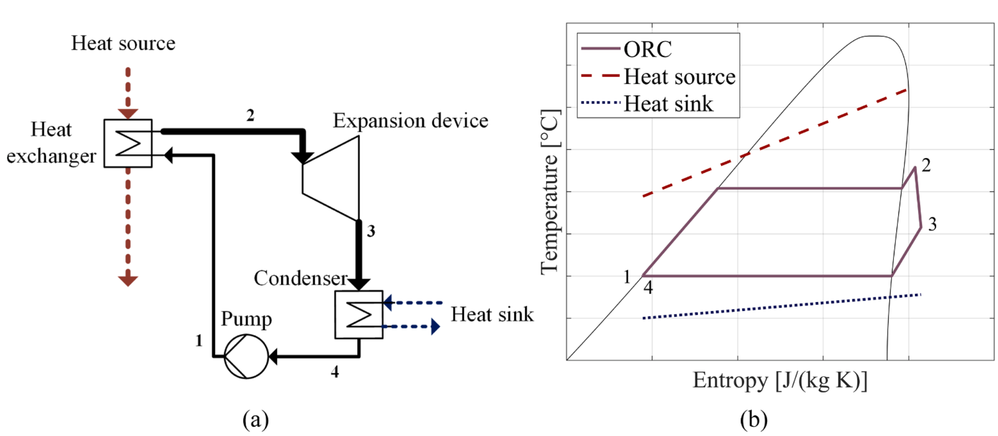

Fig. 1. (a) Flow sheet of a simple subcritical one-staged ORC, and (b) corresponding temperature-entropy diagram.

One major challenge for WHR ORC applications are the large fluctuations in temperature and/or mass flow of the available WHR source in many application cases [28]. These strong fluctuations come along with demanding requirements for both the dynamic modelling and optimal control of such variable systems [29]. For many applications with flue gas as a heat carrier, the potential utilization of the heat source is limited in order to avoid condensation of acidic flue gases [26]. The minimal possible dew point temperature depends on the exact flue gas compositions, but is typically in a range between 100 and 130 °C [26,30].

There is a tremendous potential for the utilization of stationary waste heat from the energy intensive industry. Thermal Energy Harvesting Advocacy Group of KCORC has estimated the technical potential of waste heat utilization from industry to 150 TWh_{el}/yr in EU27 [31]. Almost 25 % of this potential corresponds to heat sources with a temperature level below 200 °C, 45 % are in the range between 200 and 500 °C, and around 30 % of the potential is located above 500 °C. Pili et al. [32] carried out a detailed assessment of the techno-economic potential of waste heat recovery by ORC systems in the German energy-intensive industry (steel, cement and glass manufacturing). The authors report an economic potential of a cumulative installed ORC capacity between 227 and 435 MW_{el}. Their findings confirm the economic viability of ORC systems for WHR applications under current German market conditions.

Next to stationary industrial heat sources, also the application of ORC systems for mobile waste heat sources might be of high importance for future CO_2 savings. This pertains mainly to the automotive [33] and the maritime sector [34]. ORC systems within the automotive sector might be applied for both passenger cars [35] and heavy-duty vehicles [27]. Automotive ORC systems are characterized by strong fluctuations of the engine speed and torque, depending on the driving cycle. This results in significant and sudden short-term variations of the heat source characteristics [27]. A special challenge for automotive ORC applications is the limited available space and the need to minimize the system's weight. While many stationary WHR systems have an intermediate oil circuit, this is normally not applied in automotive applications in order to save both space and weight. The direct heat transfer from the heat source to the working fluid using a direct evaporation comes along with several challenges for the design and material characteristic of the direct evaporator [27]. While there was a strong interest in passenger cars by the automotive industry on ORC systems in the past, it appears that e-mobility is nowadays the pre-dominant R&D focus and the interest in ORC power systems has decreased. Nevertheless, mobile ORC WHR systems still have a high potential for electric and synthetic fuel applications and within heavy-duty vehicles and ships. Especially for the maritime sector, ORC WHR systems might be of high interest in order to increase the efficiency of large vessels [34]. A current example of such a commercial application is the planned installation of eight modular ORC modules by Orcan Energy on board the "Green Jade", one the largest offshore installation vessels in the world [36] and the marine installations by Climeon.

1.2.3. Biomass

Biomass covers 14 % of the world's primary energy demand. For some developing countries, this value is even up to 90 % [37]. While other renewable energy sources like wind and solar are subject to fluctuating weather conditions, biomass has the potential to significantly contribute to the base-load heat and power generation. Thus, in a renewable energy system, it might be possible to substitute parts of the power generation, which were conventionally covered by fossil fuels like coal, natural gas or oil. For instance, Algieri et al. [38] estimate the potential of agricultural residues in southern Italy (Calabria) using an ORC coupled to a combustion process, which is fueled by the lignocellulosic share of the biomass residues. They conclude that it is possible to generate between 466 and 669 GWh of electricity per year together with 1056 to 1259 GWh of thermal energy per year using CHP units. That matches the demands of at least 128,000 families for thermal energy and of 215,000 households in terms of electricity consumption in the investigated region.

However, the transportation distance of the biomass to the corresponding plant highly influences the environmental impact of the use of biomass [39,40]. Therefore, reasonable use cases for biomass-fueled power plants are usually in the medium- to small-scale range and in decentralized projects, where steam powered turbine cycles are often not cost-efficient but an ORC offers a good trade-off [2], especially in combined heat and power (CHP) systems [37]. These small-scale CHP systems, however, are typically operated in a heat-driven operation mode, which leads to a substantial amount of part load for operation of the ORC unit similar to ORCs in waste heat recovery systems [41]. In contrast to a Rankine cycle operating with water as working fluid, ORCs operating with organic fluids are characterized by high turbine efficiencies, even in part load [42], which makes ORCs especially favorable for small-scale CHP units. Even though the heat source temperature level is significantly higher compared to other common ORC heat sources like solar, geothermal or waste heat, the usage of an organic working fluid still is beneficial compared to the usage of water due to the lower pressure levels. These lower pressure levels reduce the costs of the power unit, which is especially important for small-scale applications [42].

1.2.4. Solar thermal

Solar energy can be used for both direct and indirect power generation. In the last decades, the commercial focus lay strongly on direct conversion systems by applying low-cost Photovoltaic modules. Nevertheless, research activities on solar ORC systems are attracting steady interest from academia and industry [43]. This applies especially for hybrid systems and/or CHP applications [44]. Dickes et al. [45] describe the techno-historical development of solar ORC systems. The capacities of solar ORC plants are found over a broad range between a few kW [46] and several MW [47]. The available heat source temperature for solar ORC system can range between 100 and 500 °C [43]. The achievable temperature depends mainly on the applied solar collector type [48]. The use of concentrating collectors results in higher temperatures, However, they come along with certain challenges such as a required sun tracking system and advanced material requirements [43].

A main characteristic of solar ORC systems is the periodically fluctuating heat source. In order to enable a reliable power generation, a thermal energy storage system might be installed [43]. Depending on the favored storage temperature, such a system can use either sensible [49] or latent heat storage [50]. Another promising approach are hybrid systems, combining the fluctuating heat source of the solar collectors with another reliable renewable heat source, such as geothermal [51] or biomass [52]. A recent commercial example of a solar-biomass hybrid system is installed in Brønderslev Forsyning, Denmark. The Turboden ORC plant integrates heat from two renewable energy sources: a solar field with a peak thermal capacity of 16.6 MW and two 10 MW biomass boilers [53]. Another interesting approach can be the combination of the ORC with a diffusion-absorption refrigeration system for a solar thermal cogeneration unit [54] or the integration in a renewable hybrid system for residential areas [55]. In order to further improve the commercial competitiveness of solar ORC systems, Loni et al. [43] highlight the need to further improve the economic performance, further study the optimal collector selection and carry out more experimental studies on full-scale systems.

1.3. Purpose and methodology

This section describes purpose and methodology of both the ORC database and the market survey.

1.3.1. Purpose

It is the aim of this report to present an up-to-date overview on the recent developments from the ORC industry in both a quantitative and qualitative way from different perspectives. Therefore, this publication provides an overview on (1) the number and capacity of almost all installed ORC plants worldwide as well as (2) the current status and future market expectations from an ORC manufacturer's perspective. It is intended to update the database and the market report every two years. The report will be aligned with the International Seminar on ORC Power Systems. This work is a joint effort of the Technical University of Munich (market assessment) and the Politecnico di Milano (analysis of worldwide ORC installations database). The Knowledge Center on Organic Rankine Cycle (KCORC) as the umbrella organization of the conference acts as the main contact point regarding the market report and will further exploit its results to the community.

1.3.2. Methodology

The market assessment is a compilation and evaluation of data from nearly all relevant ORC manufacturers. For this purpose, a survey has been developed, benchmarked and distributed to all relevant ORC manufacturers in order to obtain valuable insights on the current market situation. In addition to that, the expectations and prospects for the next two years were also part of the survey. In total ten manufacturers have completed the survey, representing small-, medium- and large-scale ORC manufacturers.

The original version of the world database of installed ORC power plants has been built by Thomas Tartiere and Marco Astolfi in 2016 counting more than 2.7 GW of installed capacity and more than 1700 ORC units from 27 different ORC manufacturers. A full analysis of this ORC market status database is reported by Tartière and Astolfi [56] in 2017. The database has been updated in 2021–2022 which consistently increased the number of records by adding new references from 13 ORC manufacturers (labelled with * in Table 1), while the other 18 declined to take part to the survey because they are not in the business anymore or because of confidentiality reasons. The ORC database now includes almost all plants commissioned since 1975 and a map of all references is available at https://orc-world-map.org. Table 1 reports in alphabetical order the list of the 31 ORC manufacturers that are included in the database with the number of installed units as well as the total installed capacity until February 2022. The analysis carried out in section 2 is considering plants installed until the end of 2020 and it is important to underline that this analysis always refers to installed plants and capacity since the precise information regarding the actual status of ORC projects and the actual running capacity is often not available.

Table 1
ORC manufactures included in the database. Manufacturers labelled with * updated their reference in the last four years.

Manufacturer	Capacity, kW	Plants
ABB	3′800	2
Adoratec	18′434	24
BEP - E-rational	3′732	21
Calnetix	2′478	20
Calnetix/CETY	700	5
Calnetix/Ingeco	3′125	25
Climeon*	7′320	49
Dürr Systems AG*	5′920	53
Electratherm	3′535	63
Enerbasque*	253	11
ENERTIME*	27′500	14
ENEX	9′300	1
ENOGIA*	3′400	94
Enreco	180	3
EXERGY*	476′539	50
General Electric	101′000	6
GMK	5′399	21
gT - Energy Tech.	670	2
Johnson Control	1′750	1
Kaishan	33′155	46
OPCON E.S. AB	1′995	3
Orcan Energy AG*	40′973	503
ORMAT*	2′806′220	1′226
RANK*	1′558.5	26
TAS	143′000	17
TICA*	27′720	99
TMEIC	1′000	1
TRIOGEN*	7′048	50
Turboden*	771′934	408
UTC Power	3′080	11
Zuccato*	6′460	39

2. ORC market analysis

2.1. Historical trends and current market status

Fig. 2 depicts the historical trend of installed power (Fig. 2.a) and installed plants (Fig. 2.b) since 1975 divided by application. In particular, Fig. 2.c and Fig. 2.d report the relative share of each application in the last 45 years. It is worth to highlight that the installed capacity by year remains relatively low (below 100 MW) until 2008 when it started to rapidly increase by reaching a maximum value close to 400 MW in 2015 and then stabilizing around 300 MW. Main contribution to the soar of ORC installed capacity is due to geothermal application followed by biomass - especially between 2000 and 2012 in Europe - and by waste heat recovery (WHR) in more recent years. Current cumulative ORC capacity divided by application highlight the dominant position of geothermal field (77.4 %), an almost equivalent share for WHR (11.6 %) and biomass applications (10.1 %) and a minor contribution of the other applications: waste-to-energy (0.7 %), solar (0.2 %), remote applications (0.03 %).

Regarding installed plants the annual trend is less static and shows some peaks in the past represented by a large number of micro-scale (around 1 kW) remote units installed along pipelines by Ormat while a rapid increase is achieved in last three years thanks to a large number of small-scale WHR installations. The yearly share of installed plants has been dominated by geothermal energy until 2000 (with occasional drops related to remote application), by biomass between 2000 and 2012 thanks to the soar of European market and by WHR nowadays. Current cumulative ORC installed plants is dominated by WHR (34.5 %) and remote (32.2 %) applications followed by biomass (16.1 %) and geothermal applications (15.6 %). Solar and waste-to-energy counts a small number of plants equal to 0.9 % and 0.7 % of the overall market, respectively.

2.2. Market changes in 2016–2020

Fig. 3 depicts the cumulative installed power (Fig. 3.a) and the cumulative installed plants (Fig. 3.b) from 1975 to 2020. It is interesting to note that the trend is firmly increasing and that from the last analysis in 2016 the overall ORC market increased by 40 % (+1.18 GW) in terms of installed capacity and 46 % (+851) in terms of installed plants. Actual capacity installed is close to 4.1 GW with more than 2700 installed plants. Moreover, more than 452 MW and 189 plants have been either built in the first months of 2021 or are planned for the next years. Regarding the market increase between 2016 and 2020 (Fig. 4.c) the largest increase in terms of capacity is due to geothermal application (+972 MW, +45 %) while a minor contribution in terms of capacity is due to WHR, biomass and Waste-to-Energy. The latter three fields of application also show good relative increases between 20 % and 36 %. Finally, solar capacity has doubled during the last four years but still has a nearly negligible contribution to the overall ORC world market. Regarding installed plants (Fig. 3.d) in the last four years the overall number increased by 859 units (+46.5 %), the largest share is due to WHR, which increases its installations by 630 plants (+208 %), while the other applications increased their units by around 20 % to 25 %.

2.3. ORC application size analysis

Fig. 4 depicts the trend of single unit installed capacity from 1975 for

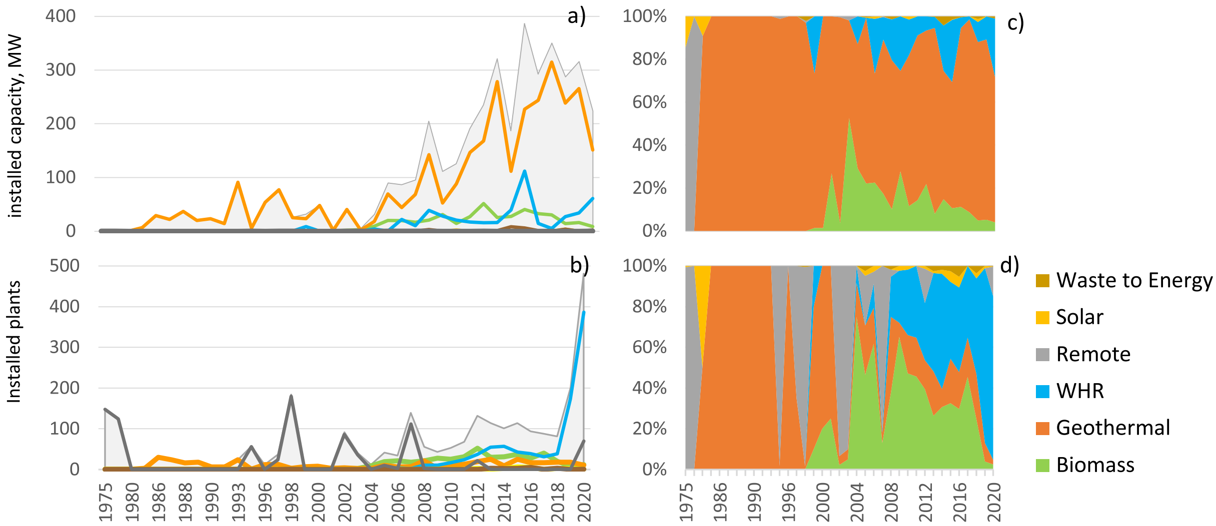

Fig. 2. Historical trend of ORC installed capacity (a) and installed plants (b) divided by applications and relative share by year (c-d).

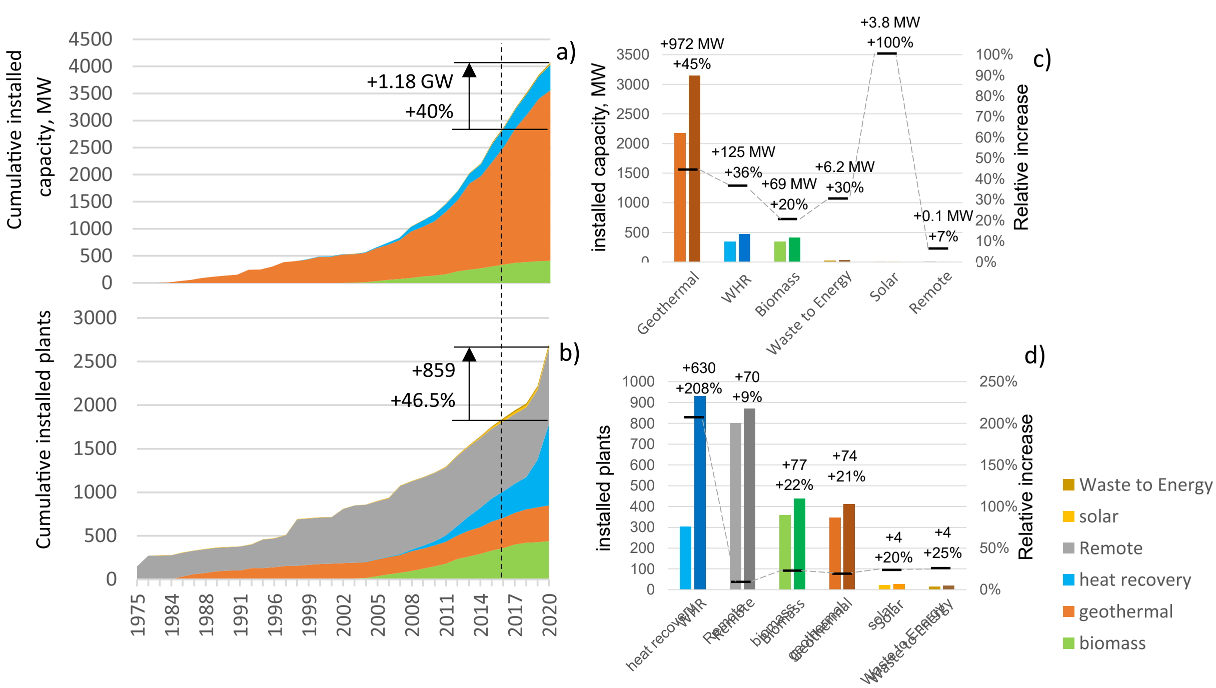

Fig. 3. Historical trend of cumulated ORC installed capacity (a) and installed plants (b) divided by applications and increase between 2016 and 2020. Market increase in 2016–2020 divided by application in terms of installed capacity (c) and plants (d).

the three main applications for ORC power systems. Colored area represents the power range from minimum to maximum while the continuous line is the average plant size installed in that year (please note that the sacle of the x-axes are different for the three applications). Geothermal power plants progressively increased in size starting from power plants in average below 5 MW until 1995 and reaching an average size of 13 MW in the last 10 years however still 50 % of the installed plants is below 4.5 MW. Maximum power plant size trend is steadily increasing with current biggest plants of around 35 MW (only one biggest plant of 50 MW single unit was installed in 2009) while minimum size is getting very low (few tens of kW). On the contrary, WHR installation started to increase in number only recently: first installations were characterized by a pretty high average size thanks to a technology transfer from biomass sector, while the trend of the last 10 years clearly shows an average unit capacity continuously decreasing with an average size of around 500 kW in spite of the presence of quite large units between 8 and 17 MW. As a result, half of the installed plants in WHR field so far has a capacity of around 100 kW. This is mainly due to presence in the last years of a large number of small size ORC manufacturers that have been able to provide a cost effective solution also for mid-scale WHR applications by installing several small units in parallel. Biomass applications show a trend which is more stable in time: maximum size progressively increased while minimum one decreases but the average size is steadily between 500 kW and 2 MW since the first installations in 2000 with half of the installed plants so far having a capacity below 1 MW. This is mainly due to the fact that biomass application is a less dynamic sector dominated by a single company (Turboden) that focused on some specific plants sized according to the European countries policy and regulation.

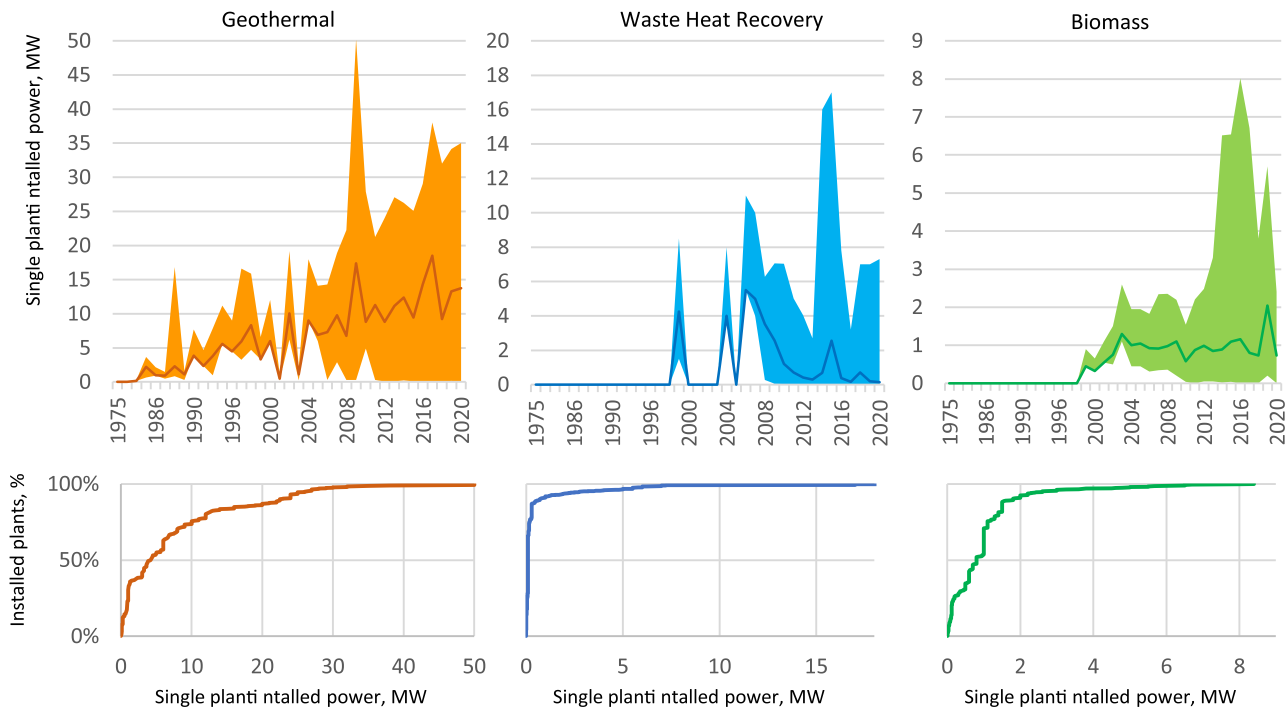

Fig. 4. (top) maximum, minimum and average (continuous line) single unit installed power over years for geothermal, WHR and biomass application. (bottom) installed power plants distribution vs plant size for geothermal, WHR and biomass application.

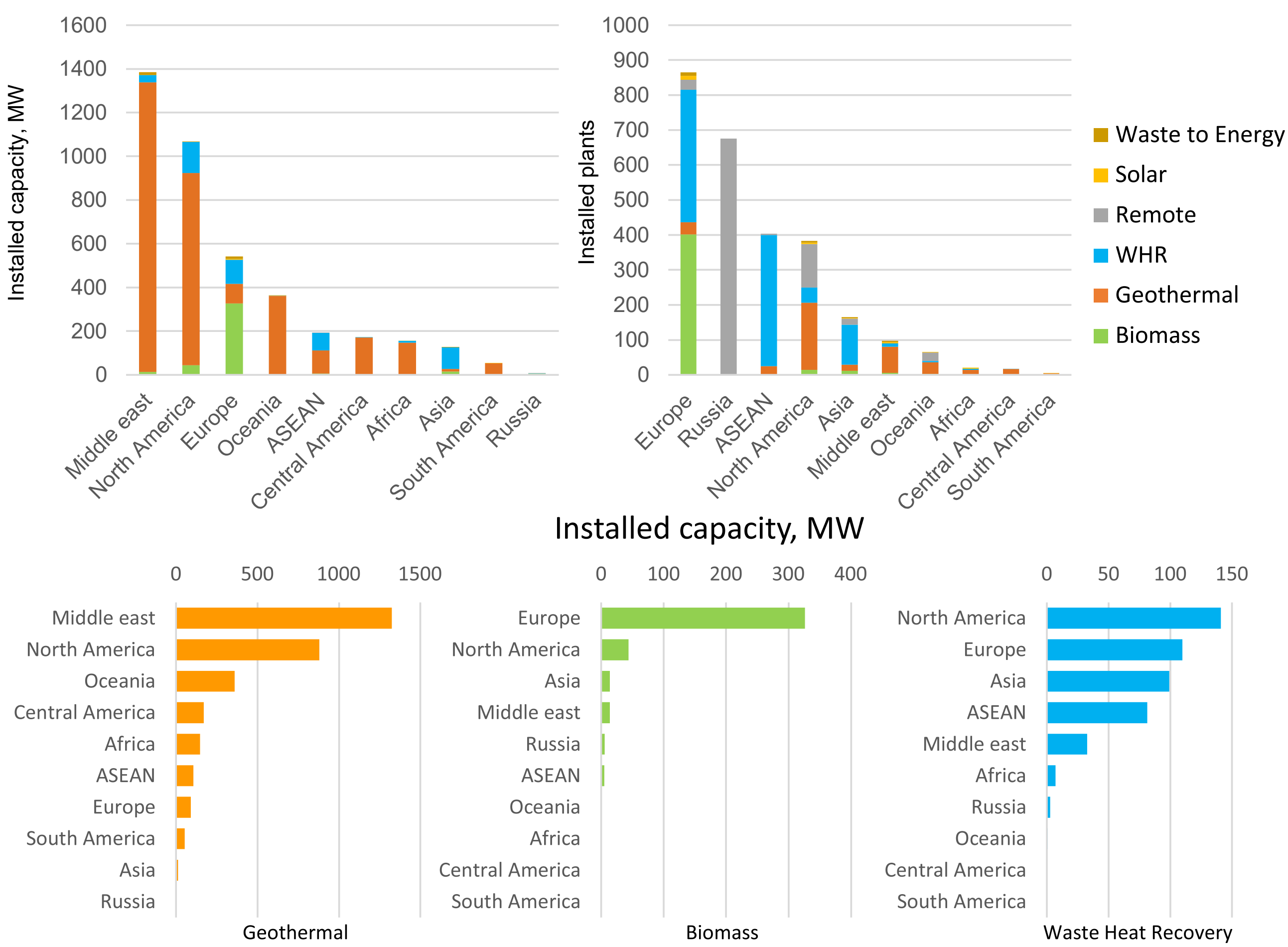

Fig. 5. Installed capacity (top-left) and installed plants (top-right) divided by application in the different macro-region worldwide. Detailed of installed capacity for different applications (bottom).

2.4. ORC market by region

Fig. 5 reports information regarding the geographical distribution of ORC plants. The prime two ORC macro regions in terms of installed capacity are the Middle East and North America thanks to the availability and the exploitation of geothermal energy followed by Europe where biomass energy is the most common technology. On the contrary, in terms of installed power plants Europe is leading since both biomass and WHR adopts relatively small power plants between 1 and 5 MW while Russia (in second position) counts for a very large number of very small remote ORC plants along gas pipelines but a very low overall installed capacity. Geothermal energy is mainly exploited in Turkey and the USA while biomass plants have been mostly installed in Europe (Germany and Italy) because of favorable incentives. WHR applications are more uniformly distributed around the world because they are coupled with industrial processes and not to the availability of a specific natural energy source.

2.5. A focus on WHR market

Waste heat recovery is the application that has shown the largest potential in the last four years in terms of installed plants + 200 % and installed capacity + 36 %. This is mainly due to the increasing attention on energy efficiency from industry, the increasing price for electricity and the availability on the market of a large variety of small-scale ORC that can be easily installed and operated on site. Fig. 6 depicts the analysis of WHR market adopting three main sub-applications: (i) WHR from primary engines with ORC as bottoming cycle (304 MW and 64 % of the market), (ii) WHR from industrial processes (159 MW, 33 %) and (iii) others (13 MW and 2.7 %). The main application is largely heat recovery from Diesel or gas engines and turbines, with more than 285 MW installed. using exhaust heat from combustion engines or turbines (hot flue gases) is generally easier than industrial heat recovery because of the low impact on the upstream process and the high attainable increase in terms of energy efficiency. ORMAT has been very active in this field with several plants of around 3–8 MW installed along gas pipelines in the USA and Canada. On the contrary, heat recovery from other type of engines is relatively small although a big market is expected for marine engines if new policy and regulation will force this sector towards the limitation of CO_2 emissions. Regarding industrial WHR the two main sectors are primary or fabricated metal production and cement & lime with a similar installed capacity of 49 MW each, while glass and chemical industry installations are around 25 MW each. These four sectors are characterized by high energy density and by the availability of a large amount of high temperature waste heat which is relatively easy to exploit on site with respect to other industrial sectors.

2.6. ORC market by manufacturer

Regarding the ORC market from an ORC manufacturer's point of view, it is interesting to underline that the three main companies, that were leading the market in 2016, were able to firmly hold their position in the last four years. They installed more than 78 % of the new installed capacity between 2016 and 2020: Ormat (+775.6 MW), Turboden (+158.2 MW) and Exergy (+156.2 MW). Each one of them increased their corresponding installed capacity by around 40–50 %. The remaining installed capacity in the last four years (87 MW) is shared between manufacturers of small ORC units that, on the contrary, largely increased their installed capacity: Orcan Energy AG (+3900 %), Enogia (+595 %), Rank (+192 %), Dürr Systems AG (+111 %), Enerbasque (+72 %) and Zuccato Energia (+60 %). Thus, demonstrating that also this type of business is sustainable and highlighting the dynamics and the large room for market growth and possibilities for new players. In this context, it is worth to highlight two cases: (1) Enertime, which commercializes plants between 2 and 3 MW, has been able to increase its capacity by 430 %. (2) Climeon and Tica which were not existent back in 2016 and have been able to install 2.7 MW and 23 MW respectively during the last four years.

3. Outlook

3.1. Business development

The business and market development is based on the feedback of the participating technology providers in the ORC2021 market survey. Considering the fact that the last two years have been strongly affected by the COVID-19 pandemic, it was important to get feedback and insights on the market development during this period from the technology providers. The results are shown in Fig. 7.

The feedback to the question on "How did the COVID pandemic affected your ORC business?" was on average 3.0 on a scale ranging from 1 (No Impact) to 5 (Negative Impact), with a standard deviation of 1.1 and a median of 3. Showing that the ORC industry is quite robust, but was definitely suffering impacts from the COVID pandemic.

The question on "How do you evaluate the current market situation in general?" was on average 3.0 on a scale ranging from 1 (Bad) to 5 (Excellent), with a standard deviation of 1 and a median of 3. This robust feedback from the community suggests that the ORC business might have experienced an even stronger growth during the last years, if COVID would not have affected global markets.

With respect to employments, the ORC market performed quite robust with the numbers of employees remaining at a rather constant level and favorably increasing. The result obtained is an average of 3.3 on a scale ranging from 1 (Decrease) to 5 (Increase), with a standard deviation of 0.7 and a median of 3.

With respect to the short-term development forecast of the ORC business the technology providers came up with the results as shown in Fig. 8.

The response to the question on "How would you rate your expectation in business development during the next two years?" was a very positive outlook with an average 3.7 on a scale ranging from 1 (Bad) to 5 (Excellent), with a standard deviation of 0.9 and a median of 4. This positive outlook of the community indicates that the ORC business is further emerging and will potentially recover quite fast from the latest COVID restrictions.

Also in terms of employments and job perspectives, the ORC

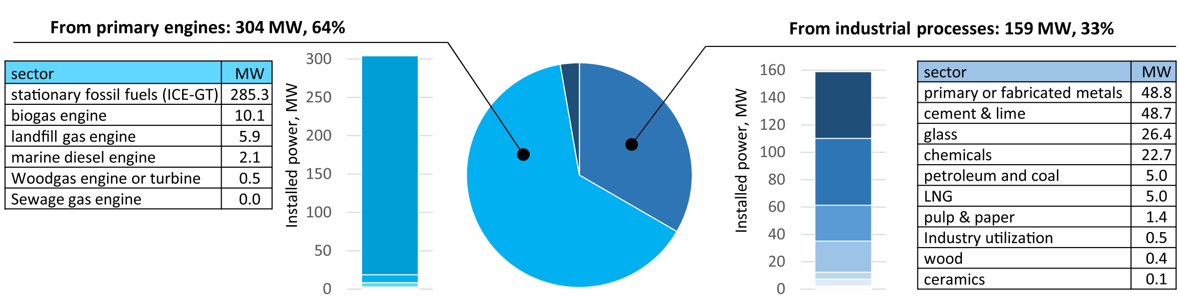

Fig. 6. WHR sector analysis.

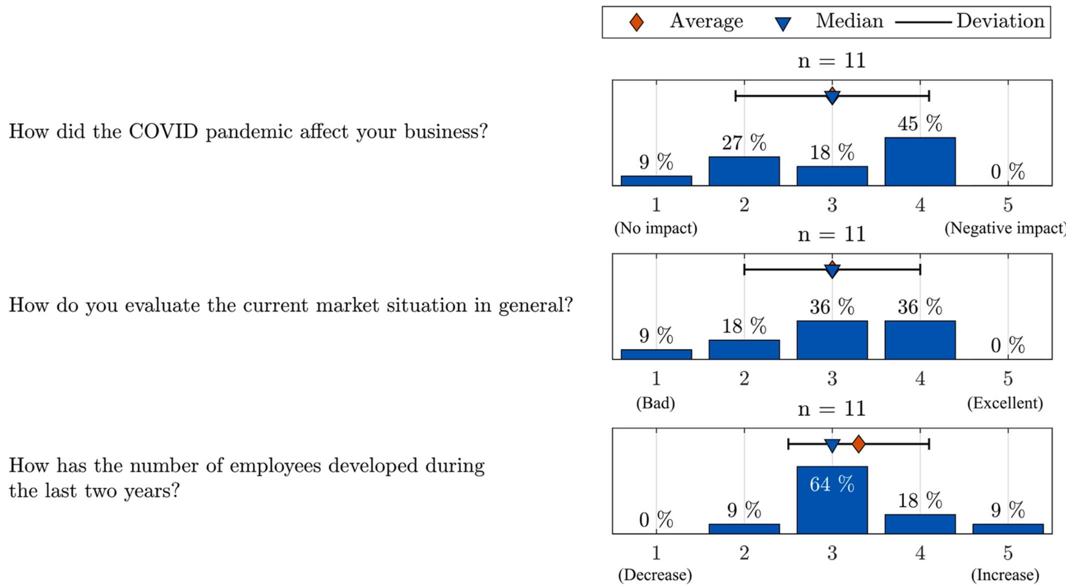

Fig. 7. Survey result on current market situation.

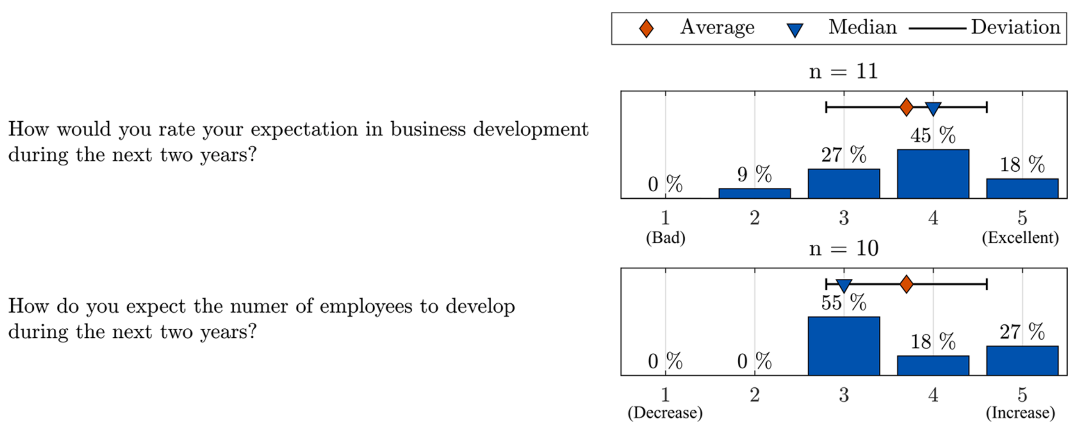

Fig. 8. Survey result on short-term future market situation.

manufacturers intend to build up capacity, as almost half of the participating ORC technology providers are expecting to recruit new employees in the near future. The result obtained is on average 3.7 on a scale ranging from 1 (Decrease) to 5 (Increase), with a standard deviation of 0.9 and a median of 3.

3.2. Market development

In order to investigate the expected future market development and to identify emerging markets in specific macro regions, the participating technology providers have been asked for their input. The results are shown in Fig. 9 and the main take-awary can be concluded as follows:

Manufacturing of components

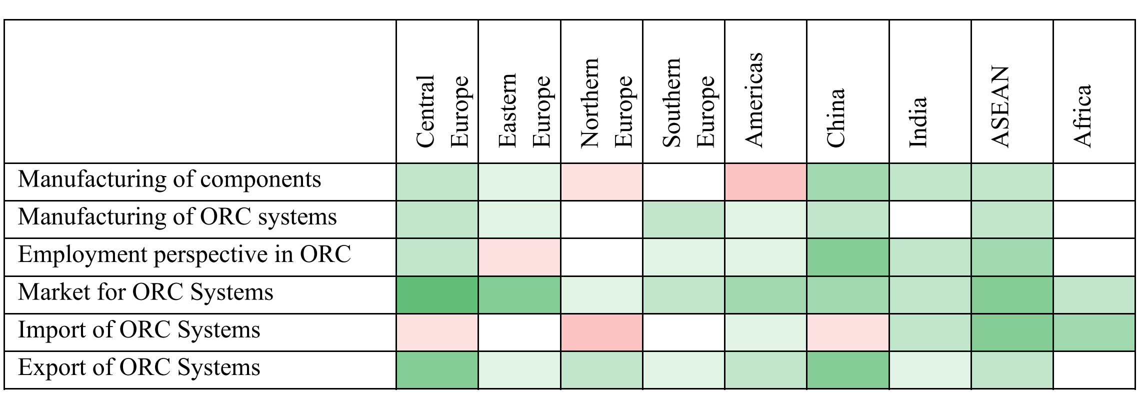

Fig. 9. Region-specific industry development. (green. increase in importance, red: decrease in importance), light to dark represents an increasing degree of change.

- The manufacturing of components will mainly increase in China.
- Also India and the ASEAN region will experience a slight increase.
- Europe will maintain its role as a component manufacturer, experiencing slight regional shifts from Northern to Central and Eastern Europe.
- The role of America as a component manufacturer is expected to decrease slightly.

Manufacturing of ORC systems

- The manufacturing of ORC systems is expected to increase almost all-over Europe, except Northern Europe.
- China and ASEAN region will also increase their importance.
- The role of Northern Europe, India and Africa is not subject to significant changes.

This general increase is in line with the positive outlook on business development highlighted previous section.

Employment perspective

- The ORC sector experiences a slightly positive employment perspective for Europe, with Eastern Europe slightly decreasing
- The main drivers in employment are most likely found in China and ASEAN region.

Market development

- A positive market development is expected on a global scale.
- Inside Europe the increase might occur in Central and Eastern Europe.
- Outside Europe, ASEAN region will increase in market development.

Import of ORC systems

- Europe's import of ORC systems will further reduce. As Europe has quite a number of established ORC technology manufacturers, they are capable to serve their home market directly.
- Similarly, China's market will have less import of ORC systems, which is due to (i) joint-ventures with European manufacturers, (ii) own capacity built-up and (iii) existing market barriers for European manufacturers.
- As the demand is rising also in other regions, their imports will increase.

Export of ORC systems

- Central Europe and China are likely to become the leading exporting regions of ORC systems.
- In parallel to that, other regions will experience slight increases, except for the African region.

Based on the input from the technology providers, the most important heat sources per region for ORC technology have been identified. The color-coded summary is shown in Fig. 10. While biomass and solar will only slightly increase during the next years, geothermal will increase especially in ASEAN region and the Americas. For waste heat recovery, significant growth rates, especially in Europe are projected mainly for small-scale units. Large-scale units in waste heat utilization will experience only a slight increase with a focus on China and ASEAN. Other heat sources than the ones mentioned above have not been further specified but play a negligible role anyways.

3.3. Research demand from manufacturers perspective

Prime focus of the ORC manufacturers is to bring their products into the field. However, innovations are necessary in order to optimize and further develop the products. Besides the more fundamental research demand, applied research close to manufacturer needs is of high interest to the ORC research community. Therefore, ORC2021 market survey asked ORC technology providers where they see the largest R&D needs. The following component- and concept-related areas have been identified:

1. High performance working fluids which are non-flammable, with low GWP and ideally suitable for high temperature-levels
2. Direct condensation with dry cooling towers
3. High performance heat exchangers for exhaust gases
4. CHP-concepts

Besides these four specific research needs mentioned above, several manufacturers see a need for a general price reduction of the technology. This includes mechanical, but also electrical components. According to Lemmens [57], for medium-scale ORC systems of 375 kW size, the main cost drivers by far are the rotational equipment with roughly 70 % of purchased equipment costs. Heat exchangers account for the remaining 30 % of the purchased equipment costs and overheads for installation and thermal oil circuit sum up to an additional 20 % each. Therefore, research on technology leaps and significant cost reductions in rotational equipment and heat exchangers are always justified. Another option for cost reduction can be achieved by a "good enough" design strategy of ORCs instead of over-engineered designs reaching for highest efficiencies. This comprises also the modular approach with off-the-shelf-products, where the trade-off between costs and efficiency is optimized for market needs.

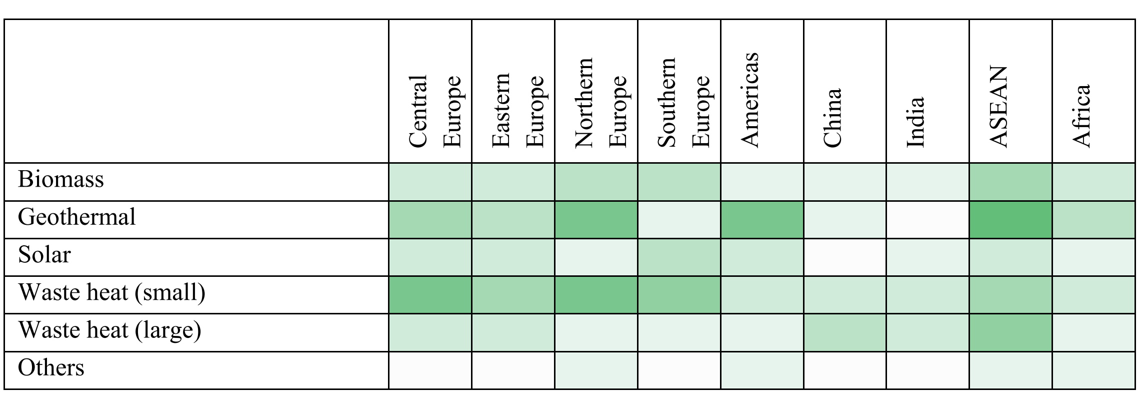

Fig. 10. Region-specific installations development. (green: increase in importance), light to dark represents an increasing degree of change.

3.4. Effective regulatory measures to increase ORC technology diffusion

In order to facilitate the transition of the current energy system, ORC technology is not only desperately needed for electricity production from geothermal or biomass, but also to harvest waste heat from industry as this potential is huge. This emerging ORC market can be accessed by appropriate regulatory measures:

1. Subsidies on capital expenditures (CapEx) have proven successful in Germany. This can act as a role model for other European countries, as the decision-making criteria for industry are short payback-periods of approximately 3 years.
2. Market based approaches:
   a. (Tradable) white certificates for implemented energy efficiency measures are considered to be effective, but have been implemented only in few countries over Europe (i.e. Great Britain, France, Italy and the Flemish Region).
   b. Reduction of free certificates in the ETS (as for 2020 still 30 % of total certificates)

Bottom line, the technology providers who participated in ORC2021 market survey identified a lack of effective national implementation of Article 7 of European Energy Efficiency Directive on energy savings obligation. A more harmonic implementation based on the suggestions/ mechanisms above is desired.

Besides this, another complex regulatory barrier has been identified: Electricity grid codes – not only in Europe, but also elsewhere, e.g. in the ASEAN region. Two potential solutions for ORC technology have been identified:

a. Standardization and unification
b. Liberation for ORC units up to a certain MW-size-range from these grid codes

4. A spotlight on waste heat recovery from energy intensive industry

Sustainability aspects and financial interests are clashing in the WHR market. On the one side, there is the need to reduce emissions and to increase the energy efficiency. On the other side, the investment framework of industries is not in line with investments in energy infrastructure. This topic and the arising challenges for the ORC technology was intensively discussed on the panel debate with experts from ORC technology and stakeholders from energy intensive industries at the ORC2021 conference. The following sections provide a holistic summary of this debate.

4.1. Investment decisions

The priority of the process and manufacturing industry lies mainly on their respective core process and the products. Therefore, investments in optimization measures close to this core production process are preferred. Typical examples for such optimization measures from the oil and gas industry are fuel-steam integration and improved catalyst performance.

Based on this, it also needs to be born in mind that the process and manufacturing industry targets low payback periods of 3–5 years. This investment framework results from the fact that these industries can hardly commit their plant operation for longer periods or time horizons, as their business is subject to rapid market developments and uncertainties, like the COVID pandemic or global geo-political uncertainties. The investment horizons for energy supply and infrastructure however, is at least 10–12 years, as they are usually intended to supply electricity in the long-term for time horizons of several decades.

Therefore, low specific investment costs in €/kW of electricity are necessary to meet the short payback periods. Besides the specific investment costs, high full load operation hours can be an alternative lever to achieve the short payback periods (i.e. greater than 5000 h/a). Although waste heat is considered to be free of charge, the number of industrial use cases where ORC technology diffusion happens without any additional incentives is limited.

When looking more into the costs for peripheral infrastructure, quite some investments into the WHR system are necessary. Flexibility by means of co-generation can be an interesting option to increase waste heat utilization and thus profits. At the same time, the costs for peripheral infrastructure can be split to two commodities: heat and electricity.

In order to facilitate the decision-making for the energy intensive industry, a couple of ORC manufacturers follow a quite interesting approach: Contracting solutions offered by energy service companies. In this scenario, the industry company commits electricity purchase over a specified period from the energy service company, which is in charge for engineering, commissioning and operation of the ORC unit. In a few cases, the ORC companies themselves offer such solutions with their subsidiaries. With small and modular systems, the energy service company (ESCO) has the opportunity to relocate the ORC system to another customer, when one contract is terminated or expired. This would allow for shorter contract periods. Larger tailor-made plants can offer full operation and maintenance packages to their customers. The downside of ESCOs is that they might have an additional overhead for their engineering and costs of financing, which poses challenges on the competitiveness and low specific investment costs.

4.2. Installation risks and challenges

The increasing risk of outages by installing additional components and systems needs to be hedged. Technical solutions need to be in place to avoid any un-scheduled downtimes or interruptions of the main process, as even short-term downtimes can cause significant economic losses. Compared to these costs, the installation costs of the ORC as well as the potential revenues from the ORC operation are comparatively small. ORC installations outside battery limit are less risky. On the other hand, waste heat streams outside battery limit are more difficult to capture. Another key aspect is that the ORC technology has reached a significant maturity, but neither the entirety of process industry nor the entirety of engineering consultants are fully aware of this fact. Solutions and best practices need to be disseminated more.

Another important aspect relates to retrofitting actions of existing plants in existing industry branches, which is likely for Europe where hardly any new-built plants are found. To provide ORC solutions to existing plants, which have never been designed for additional components or the integration of new technologies, compactness and a small footprint is key. An alternative might be the transport of the waste heat to the proximity of the process plant, where the space constraints are less challenging. Greenfield installations, as they are found for instance in China, can integrate energy efficiency solutions easier.

4.3. Waste heat accessibility

Moreover, it has to be born in mind that only parts of the available waste heat is easily exploitable. The difference between theoretical and technical potential needs to be considered for this purpose. As an example, from the total available waste heat of a fully integrated steel making process, 35 % of this heat is already reused in the process; another 10 % is considered to be readily available for exploitation. The other 55 % of waste heat is considered as "hard to capture", as their recovery is not yet financially attractive or economically viable, because this heat is either at low temperatures, or distributed across the plant with low capacity sub-streams, or needs to be recovered from (by-) products, such as solids. This "hard to capture" waste heat can be exploited, at least in parts, by small and modular units with a small footprint. This is supported by the data presented in Fig. 3, where more than 640 plants have been installed in WHR sector during the last four years resulting in an average installation size of less than 200 kW_{el}. Future technologies should target low temperature applications in order to increase the utilization potential of the "hard to capture" waste heat.

5. Conclusions and outlook

This work provides a detailed and novel update about the development of the installed ORC systems and the ORC market worldwide. For the first time since 2017, an extensive update on the worldwide ORC market review is provided. All relevant ORC market manufacturers have been approached in order to submit data about their realized ORC projects during the last years and to participate in a market survey. While all main ORC companies have provided data and participated in the survey, a potential limitation might be that some minor ORC manufacturers have not been approached and/or participated (cf. Table 1). Especially regarding the Asian market, some potential manufacturers might be not included in the survey. By representing the input of around 2900 projects, it provides crucial insights on the current market developments and trends. In combination with the market survey, more detailed insights on the current and future market situation can be presented. The main conclusions of this report are:

- At the end of 2020, the cumulated ORC installed capacity was 4.1 GW. Since 2016, the overall ORC market increased by 40 % (+1.18 GW) in terms of installed capacity and by 46 % (+851) in terms of installed plants. A consistent increase of both capacity and installed plants is expected in the next two years from plant currently under construction.
- Regarding the capacity increase between 2016 and 2020, the largest increase is due to geothermal application (+972 MW, +45 %) mainly in Middle East and North America, while waste heat systems have the largest growth concerning the number of installed systems (630 plants, + 208 %) as demonstration of the large interest for energy efficiency and energy savings worldwide.
- The results of the market survey highlight that, despite the impact of the COVID-19 situation, the current market situation is considered as robust and that the majority of the manufactures have positive expectations concerning the development of both the ORC market as well as the employments during the next two years.
- Central and Eastern Europe as well as the ASEAN region are rated as the regions with the highest growth potential. The most relevant heat sources for the coming years are regarded as geothermal energy and small-scale waste heat.
- Waste heat recovery from industry is an emerging field of application for ORC technology. Energy service companies can bridge the gap between the technology providers and the customers by facilitating investment decisions.

This report will be the starting point of regular market report updates aligned with the International Seminar on ORC Power Systems under the umbrella of the Knowledge Center on Organic Rankine Cycle Technology (KCORC). The market developments within the ORC industry are intended to be presented on a regular basis to the whole ORC community. In the future, further features are intended to be incorporated in the reports. First, during the data collection process of new ORC installations, more specific data on the heat source characteristic, working fluid, plant concept, etc. might be gathered. Secondly, expert interviews with relevant actors from the ORC market might be carried out in order to obtain valuable additional insights on the challenges, opportunities and future market developments. Thus, further interesting insights might be revealed by an extended methodology and data collection.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The database that has been used is confidential.

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Some of the authors are also organizers of the conference www.orc2021.com. This paper is intended to complement the VSI of www.orc2021.com as a review paper on the current status of ORC market. The main author serves as one of the guest editors for the VSI.

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